Atmospheric Environment 174 (2018) 122–131

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

The theory-practice gap of black carbon mitigation technologies in rural China

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ARTICLE INFO

Keywords:
Black carbon mitigation
Cost gap
Climate change
Air pollution
Environmental policy

ABSTRACT

Black carbon mitigation has received increasing attention for its potential contribution to both climate change mitigation and air pollution control. Although different bottom-up models concerned with unit mitigation costs of various technologies allow the assessment of alternative policies for optimized cost-effectiveness, the lack of adequate data often forced many reluctant explicit and implicit assumptions that deviate away from actual situations of rural residential energy consumption in developing countries, where most black carbon emissions occur. To gauge the theory-practice gap in black carbon mitigation – the unit cost differences that lie between what is estimated in the theory and what is practically achieved on the ground – this study conducted an extensive field survey and analysis of nine mitigation technologies in rural China, covering both northern and southern regions with different residential energy consumption patterns. With a special focus on two temporal characteristics of those technologies – lifetimes and annual utilization rates, this study quantitatively measured the unit cost gaps and explain the technical as well as sociopolitical mechanisms behind. Structural and behavioral barriers, which have affected the technologies' performance, are discussed together with policy implications to narrow those gaps.

1. Introduction

Large developing countries like China and India face dual challenges of mitigating greenhouse gases emissions and combating air pollution, which could serve as two driving forces for black carbon mitigation (Xu, 2017). Though having a short residence time in the atmosphere, black carbon can have significant warming impacts on the climate (Bond et al., 2013; Ramanathan and Carmichael, 2008). In a 20-year timespan, its global warming potential (GWP) is estimated to be 3,200, which will gradually drop to 900 in a 100-year time horizon (Bond et al., 2013). Scientists have called for black carbon mitigation to win time for politically tougher, economically more costly climate change mitigation (Shindell et al., 2012; Shoemaker et al., 2013). Some suggest that black carbon mitigation can be one of the 50-year stabilization wedges, equivalent to 25 billion tons of carbon (Grieshop et al., 2009; Pacala and Socolow, 2004). In addition, black carbon emissions are associated with adverse health effects because it is a component of fine particulate matter ($PM_{2.5}$) (Shindell et al., 2012; Highwood and Kinnersley, 2006; Kopp and Mauzerall, 2010). Thus, black carbon mitigation also plays an important role in public health management. Regarding the emission source, in developing countries, fossil fuel combustion (traffic combustion) and residential combustion constitute two major sources of black carbon emission (Liu et al., 2011; Shen et al., 2015).

More efforts are still needed to mitigate black carbon emissions. Though six major greenhouse gases are regulated by the Kyoto Protocol and halocarbons are largely addressed in the Montreal Protocol, black carbon—as one of the short-lived pollutants with strong climate effects—remains largely unregulated. In response to this regulation gap, there are increasing international efforts to tackle this problem including the Global Alliance for Clean Cookstoves hosted by the United Nations Foundation since 2010 and the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC) launched by the United Nations Environment Programme in 2012. From a global perspective, controlling emissions in developing countries has been proved to be more cost effective than that in developed countries (Baron et al., 2009). With a large share of black carbon emissions in developing countries coming from the residential burning of biomass and coal, many international and domestic efforts have been directed to improving energy efficiency and switching to clean fuels (Edwards et al.,

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https://doi.org/10.1016/j.atmosenv.2017.11.050
Received 9 May 2017; Received in revised form 16 November 2017; Accepted 27 November 2017
Available online 28 November 2017
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2004).

Tackling a problem as complex as black carbon mitigation requires both policy and technical solutions (Xu and Liu, 2016). Policy solution depends on active engagement of governments. Though individual choices of fuels and technologies are closely related to income level and other socioeconomic factors (Pachauri and Jiang, 2008; Johansson et al., 2012), governments can influence a society's energy structure by deploying a wide range of policy instruments. Some of those instruments are market-based, with governments providing extra economic incentives and financial supports while leaving major decisions to consumers (Rai and McDonald, 2009). Other approaches may take the form of national planning or compulsory regulations (Song et al., 2014; Sinton et al., 2004). Technical solution, on the other hand, involves assessing mitigation technologies and identifying cost-effective measures. Researchers have developed different modelling tools, especially those bottom-up ones with marginal abatement cost (MAC) curves, to quantitatively estimate an optimal set of cost-effective mitigation technologies and communicate their findings to policymakers.

Though the legitimacy of mitigation policy is hinged on the reliability of scientific models, many explicit and implicit assumptions included in those models render the findings less reliable and instructive than they would otherwise have been. Modelling involves a vast array of uncertainties, and the existence of many reluctant yet unverified assumptions has led to a widening gap between different model estimates and between theoretical and real-world (Farmer et al., 2015; Dai et al., 2016; Jefferson, 2014). Revesz and others (Revesz et al., 2014) pointed out one of the gaps—a lack of understanding of responses in developing countries—has caused the underestimation of climate change damage in social-cost models. Gillingham and others (Gillingham et al., 2015) conducted a comprehensive study of uncertainties in climate change by using a multi-model comparison and found that “parametric uncertainty is more important than uncertainty in model structure”.

Scientists working on MAC curves also need to deal with uncertainties and their impacts on the theory-practice gap. Part of the uncertainties are caused by insufficient information on the costs of individual technologies, which are critical for mitigation modelling and can vary substantially across technologies and regions (Baron et al., 2009; Rypdal et al., 2009). This problem of lack of data is common especially in developing countries, where most of black carbon emissions occur. Very often unit mitigation costs for various technologies, hereafter referred to as unit costs for simplicity, are extrapolated from those of developed countries, which can result in a biased estimation of the costs in developing countries (Rypdal et al., 2009). Moreover, in developing countries including China, India, Mongolia, and South Africa, the overall thermal performance of stoves was tested under narrowly defined operation conditions, and systematic and conceptual errors have been found in those stove testing standards and protocols (Zhang et al., 2017). Systematic errors, inconsistent measurement, and lack of comparability also increase the difficulty for modelling.

Part of the theory-practice gap is caused by a complex array of socioeconomic barriers. Some well-known discussions on those barriers can be found, for example, in the studies of energy efficiency (Hirst and Brown, 1990; Dietz, 2010; Gillingham et al., 2009). Especially for rural energy consumption where much of black carbon emissions occurs, in practice there is always a gap between what the optimal levels are in technological potential and what can be achieved on the ground. Scholars attribute the efficiency gap to two types of barriers—structural barriers and behavioral barriers (Hirst and Brown, 1990). Behavioral barriers originate from energy end-users’ attitudes, perceptions, and incentive, whereas structural barriers are often rooted in government policies and organization practices (Hirst and Brown, 1990). Because of those structural and/or behavior barriers, energy efficient technologies that can potentially reduce fuel consumption may not be well adopted. The same structural and behavior barriers can explain the gaps in other energy-related parameters.

Due to data unavailability, many researchers had no choice but to build models by using extrapolated data and ideal scenarios to estimate mitigation costs, construct bottom-up MAC curves, and evaluate policy measures (Kesicki, 2010). Take the assessment of household biogas digesters in China as an example. When calculating the unit costs of this technology, the lifetime of a digester is assumed to be approximately 20 years, which is close to its maximum potential lifespan (Yang and Chen, 2014; Wang and Zhang, 2012). This kind of assumptions needs to be reviewed to increase the accuracy of modelling and simulation. If the assumptions deviate greatly from the reality, significant errors can occur, which may in turn lead to false conclusions and a problematic course of public action. Considering the poor emission database in developing countries, the gap between theoretical estimation and ground truth and its implications for policy-making do deserve special attention.

Most researchers admit the existence of those gaps, but few studies have conducted quantitative analysis to examine the key factors that affect the magnitude of the theory-practice gap in black carbon mitigation. To improve our understanding of real-life situations, we conducted an extensive field survey and analysis of nine black carbon mitigation technologies in rural China, covering both northern and southern provinces with different residential energy consumption patterns. This study aims to quantitatively measure unit mitigation costs of different technologies on the ground and to assess the theory-practice gaps. The sociopolitical mechanism behind those gaps will also be examined together with the discussion of their policy implications. The rest of the paper is organized as follows. Section 2 introduces data and methodology. Section 3 quantifies the theory-practice gaps of nine black carbon mitigation technologies for providing cooking, space heating and water heating services. Section 4 explains the gaps by focusing on two influential factors—lifetime (the number of years that a technology is or will be utilized before suspension) and annual utilization rate (the ratio of days in a year that a technology is in use to the total days that it could be used). Section 5 discusses the sociopolitical mechanisms behind those gaps.

2. Data and methodology

2.1. Data

For examining the unit cost gaps of various technologies in rural China, a household survey was conducted in three provinces—Hebei, Guizhou and Guangxi. Hebei province is located in the northern part of China whereas Guizhou and Guangxi provinces are located in the south. A total of seven counties, 24 villages and 695 households were visited during the periods between the years 2014 and 2015. The basic information of the surveyed sites are summarized in Table 1 and their geographical locations are shown in Fig. 1. Household questionnaires were used to collect basic quantitative information, including the number of permanent residents, types of used technologies, the lifetimes and annual utilization rates of those technologies, and annual fuel consumption (such as straw, firewood, coal and others). Semi-structural interviews were conducted to collect qualitative data, including the reasons for shorter-than-expected lifetimes and annual utilization rates. It is worth noting here that instead of asking people about their annual energy assumption, this study asked the number of permanent residents in order to estimate the household's basic energy consumption. That is because each household uses a variety of technologies simultaneously which makes it difficult to distinguish whether the reported fuel consumption represents that of baseline technologies, or that of mitigation technologies, or a combination of the two. Besides individual villagers, village heads and the managers of centralized biogas systems were also interviewed to gain insights into the issues related to the organization and management of the mitigation projects.

Although the 24 villages and 695 households can hardly provide comprehensive representativeness of entire rural China with nearly 600

Table 1
Statistics on the surveyed sites.

Province	County code	County	Village code	Village	Sampled households	Total
Hebei	1	Yi	1	Beiguantou	55	263
			2	Zhouzhuang	59	
	2	Chengde	3	Dongzhuang	49	
			4	Beigushan	57	
			5	Badaogou	43	
Guizhou	3	KaiYang	6	Sanhe	12	320
			7	Liuyu	8	
			8	Yushang	13	
			9	Maojiayuan	21	
			10	Daya	70	
	4	Zunyi	11	Qingyuanju	65	
			12	Houba	7	
			13	Fengyuan	14	
			14	Lianhua	23	
			15	Chiping	25	
			16	Leshanju	8	
	5	Xixiu	17	Bashi	30	
			18	Jiulongtun	15	
			19	Qingjiang	9	
Guangxi	6	Wuming	20	Laipa	16	112
			21	Qingjiang	30	
	7	Guanyang	22	Zhongxiu	16	
			23	Shunxi	27	
			24	Yutang	23	

million people and heterogeneous conditions, the detailed household survey data could still represent a decent step forward from the current information dearth of quantitative unit cost gaps of black carbon mitigation technologies. Furthermore, in order to maximizing their representativeness, the sampled provinces were selected based on two criteria. First, the data should include both northern and southern regions to cover a variety of energy uses. It is important to capture the variation because energy consumption structure of rural households

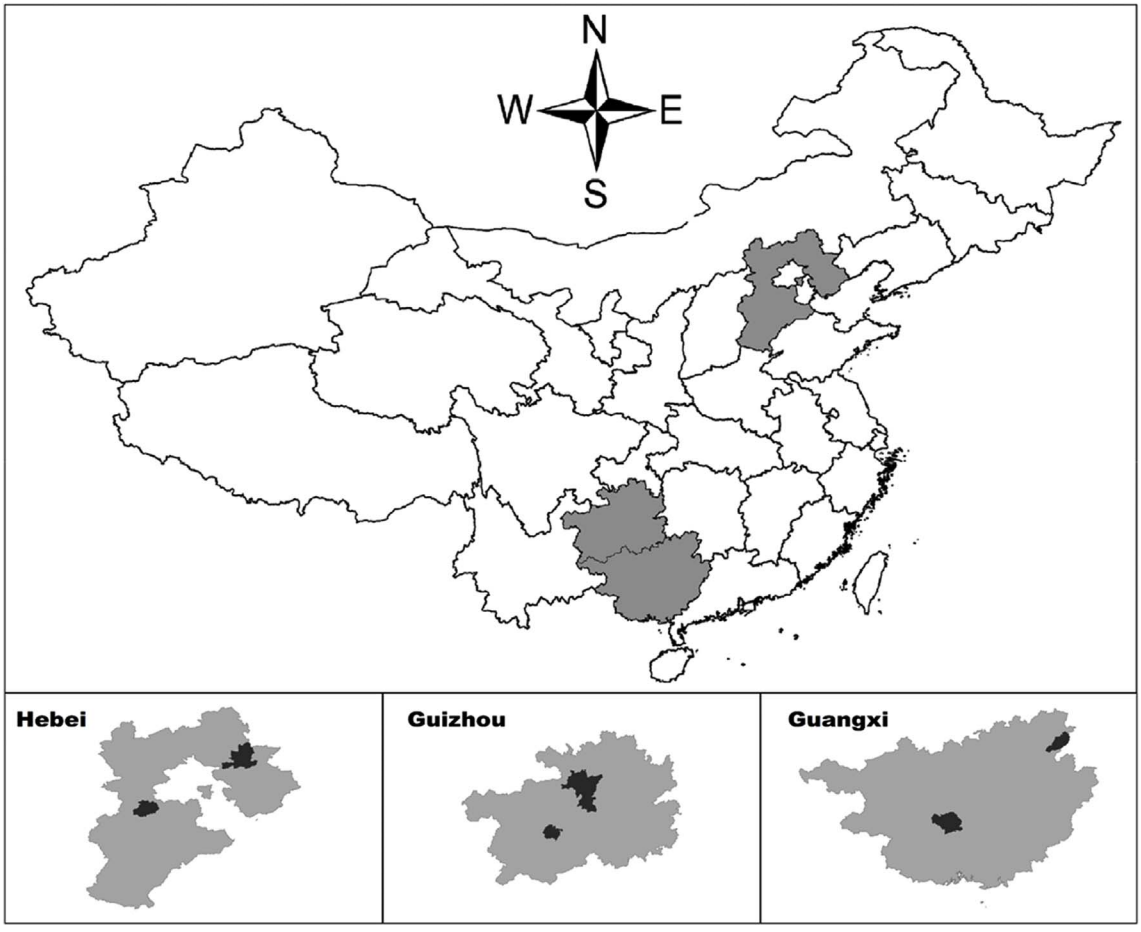

Fig. 1. The locations of counties (highlighted in black) and provinces (highlighted in grey) where the surveyed villages are.

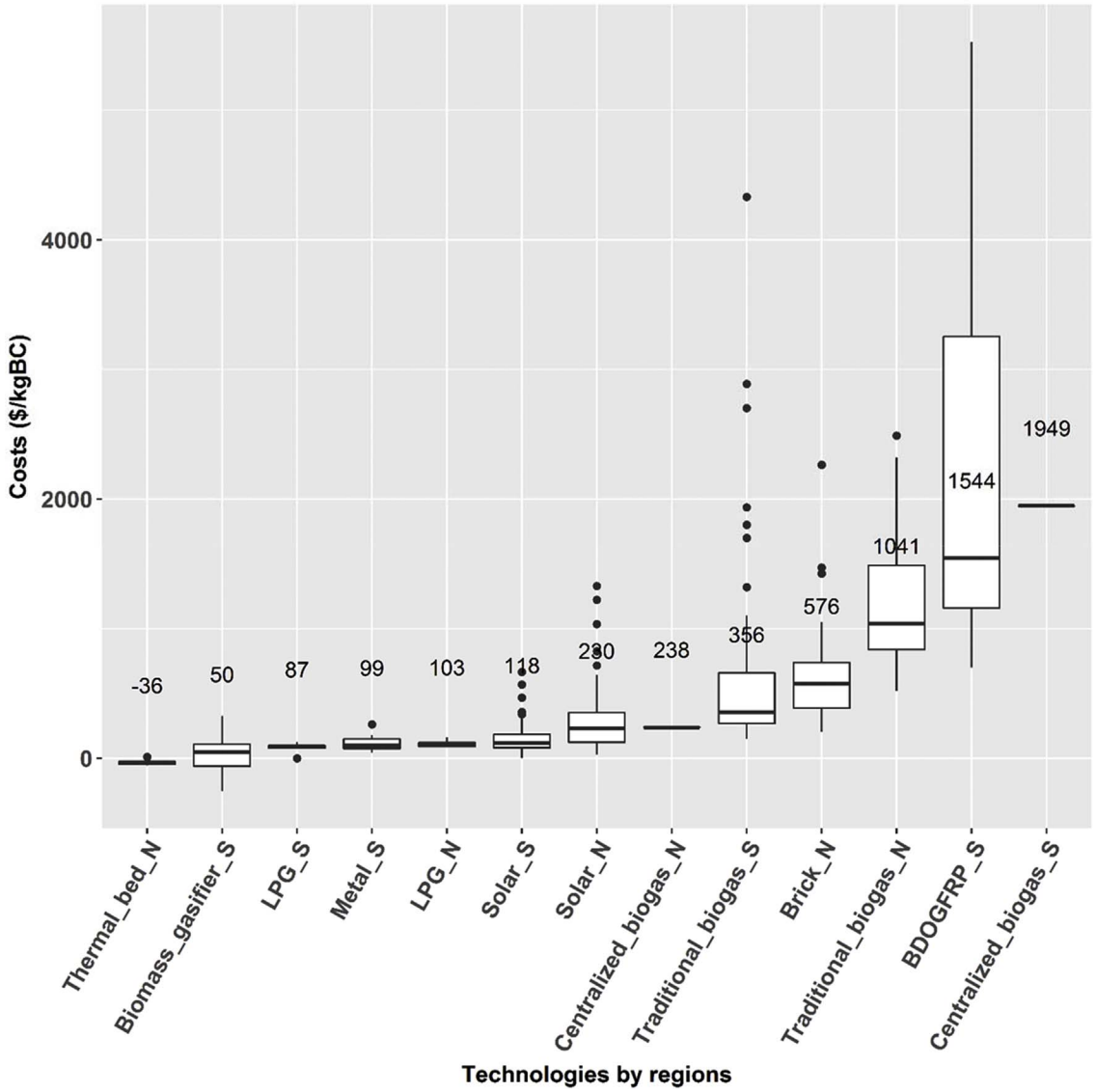

Fig. 2. Ranking of in-practice unit costs of nine mitigation technologies ("N" refers to the northern region (Hebei province) and "S" the southern region (Guizhou and Guangxi provinces). The horizontal lines in the boxes and the numbers show the median values of the in-practice unit costs. The bottom and top of the boxes are the first and third quartiles. Outliers that are more than 1.5 times the inter-quartile range away from the box are shown as dark points.).

can be very different between the north and south sides. For example, heating devices are critical for regions located to the north of the Qinling-Huai River Line with cold winter, while its importance may decrease in southern regions where winter is mild. Second, the selected provinces should be relatively big black carbon emitters in the residential sector, and potentially have a wide range of technologies and devices with black carbon mitigation potential. According to the black carbon emission inventory for Chinese provinces in 2000, in the north, Hebei province ranked second in the residential sector emission, which was 71.6 Gg. This is only secondary to Shanxi province, whose emission was 74.1 Gg (Cao et al., 2006). In the south, the emission from neighboring Guizhou and Guangxi provinces (41.7 Gg and 18.8 Gg respectively), if combined, was higher than the third largest emitter Shandong province (57.4 Gg) or the largest emitter in the south Hunan province (45.5 Gg) (Cao et al., 2006).

The survey covered nine technologies that were related to black carbon emission reduction. Based on energy services, they were further classified into three categories—cooking, space heating and water heating. For cooking, there were six technologies including improved brick stove, improved metal stove, centralized biogas system, traditional household biogas digester (distributed biogas system), biogas digester of glass fiber reinforced plastic, and liquefied petroleum gas stove (LPG stove). For space heating, two technologies were surveyed to include biomass gasifier and elevated thermal bed. Water heating involved only one major technology that was solar water heater. As part of black carbon mitigation efforts, those technologies represent two different emission reduction mechanisms, one aiming at improving energy efficiency of the existing technologies (such as improved brick stove, improved metal stove, and elevated thermal bed) and the other focusing on switching to clean fuels (such as biogas digester, biomass gasifier and LPG stove).

2.2. Estimating the theory-practice gaps

Unit costs of black carbon mitigation ($/kg BC) were calculated for the nine technologies by adapting Equation A. II.7 in the IPCC's Fifth Assessment Report (Krey et al., 2014). Different from the IPCC equation, this study focused on the amount of black carbon emission reduced by the measure annually rather than the amount of energy saved.

Unit cost reflects the cost differences between baseline and alternative technologies. The choice of baseline technologies is provided in Section S1 in the Supplementary Material. Not only were the nine

technologies examined, differences between the northern and southern provinces were also compared and discussed. Unit cost is composed of two parts, being annual mitigation cost ($) and annual amount of black carbon reduction achieved by the technology (kgBC). The annual mitigation cost ($) can be further divided into levelized investment cost and annual operation and maintenance costs (including input and labor costs). The discount rate used in this paper is 8%, and the exchange rate is 1CNY = 0.15 USD. The equation and calculation process of the levelized cost of avoided black carbon emissions or unit mitigation costs ($/kgBC) are provided in Section S2 in the Supplementary Material.

To examine the gap between the in-theory and in-practice unit costs, this study paid special attention to two temporal variables—one is the lifetime (T) and the other is the annual utilization rate (AR). The in-theory unit cost was calculated with the ideal lifetime and ideal annual utilization rate listed in academic studies, while the in-practice cost was calculated with the actual lifetime and actual annual unitization rate collected during our fieldwork. Among the nine technologies, three technologies had censored lifetime data, and their median lifetime values, estimated by the Kaplan-Meier estimator, were used as the actual lifetimes (Section S3 in the Supplementary Material). The unit cost gap between the two values was then standardized:

$$Gap^{m}_{hh,reg} = \frac{(UC^{m}_{hh,reg})_{in-practice}}{(UC^{m}_{hh,reg})_{in-theory}} - 1 \quad (1)$$

A shorter-than-expected lifetime (T) leads to a higher capital recovery factor and a higher levelized investment cost, which in turn causes a gap in unit costs. In other words, the shorter the actual lifetime of a technology is, the larger the gap will be. A lower-than-expected annual utilization rate (AR) means less black carbon is reduced each year, which also causes a gap in unit costs. That is to say, the less frequently a technology is being used within one-year span, the larger the gap will be.

To avoid the influence of outlier values and skewed distribution, median values were selected for all the following comparisons and discussions.

3. The theory-practice gaps

The in-practice unit mitigation costs of the nine technologies are illustrated in Fig. 2. For cooking, centralized biogas system (South) has the highest unit cost, which is 1949 $/kgBC, while its in-theory unit cost is 350 $/kgBC. It is then followed by biogas digesters of glass fiber reinforced plastic (BDOGFRP, South) with a unit cost up to 1544 $/kgBC in comparison with the in-theory unit cost of 32 $/kgBC. The lowest unit cost is found in LPG stove (South) that is 87 $/kgBC, the same with its in-theory cost. Among space heating technologies, biomass gasifier (South) has a greater unit cost of 50 $/kgBC compared with -36 $/kgBC for elevated thermal bed (North). Their in-theory unit costs are -97 $/kgBC and -36 $/kgBC respectively. Solar water heater's unit cost falls between 118 $/kgBC and 230 $/kgBC while its in-theory cost ranges from 80 $/kgBC to 110 $/kgBC. The gaps between in-theory and in-practice mitigation costs are shown in Fig. 3. Biogas digesters of glass fiber reinforced plastic (South) shows the biggest gap whereas liquefied petroleum gas, centralized biogas system (North), and elevated thermal bed (North) have zero gaps.

Six technologies are used for cooking in rural China, and they have different unit cost gaps (Table 2). The biogas digester of glass fiber reinforced plastic (South) has the largest gap among all technologies, which is 69.13. It is believed to be an improved type of biogas digesters. Different from traditional concrete digesters which requires constant repair to avoid gas leakage, this type of biogas digesters can significantly reduce maintenance burden on local households. However, the large gap indicates that its actual performance is far from ideal. The second largest gap of 10.53 is found in improved brick stove (North). Its overall thermal efficiency of the improved brick stove in theory is between 25% and 30%, but in reality its efficiency remains below 20% (Li et al., 2005). The large gap sheds light on significant differences between theory and practice regarding its lifetime and annual utilization rate.

Large gaps are also found in traditional household biogas digester (North), centralized biogas system (South), and traditional household biogas digester (South), which are 6.43, 4.57, and 1.04 respectively. Biogas digesters are promoted in rural China because of their low input cost—only requiring animal/human waste as input for energy generation. Depending on operating conditions and stove design, the overall efficiency of biogas stove can vary between 20% and 56% (Bond and Templeton, 2011), compared with 10%-15% of the traditional brick stove (Li et al., 2005). However, the existence of large gaps suggests that those biogas systems perform much below the optimal level in rural setting. Their in-practice costs turn out to range between 1949 $/kgBC and 238 $/kgBC, higher than LPG stove and improved metal stove.

Smaller gaps within the range of 0–0.17 are observed in improved metal stove (South), centralized biogas system (North), and LPG stove, which indicates that those technologies were relatively well adopted by rural households. The improved metal stove was widely promoted for improving energy efficiency in the south of China. Compared with the 10% thermal efficiency of traditional ones, its thermal efficiency can reach 20% (Shen et al., 2015). LPG, as one of the cooking devices, is the most efficient energy alternative to traditional fuels. In contrast to traditional biomass-based stoves, its thermal efficiency can be as high as 55% (General Administration of Quality Supervision Inspection and Quarantine of the People's Republic of China, 2007). The zero gap in centralized biogas system (North) is a special case, quite different from other biogas systems. Further details will be discussed in later sections.

For space heating, two types of technologies—biomass gasifier stove and elevated thermal bed—are examined. Biomass gasifier (South) has the biggest theory-practice gap, which is 1.10. Biomass gasifier has been widely promoted for energy efficiency improvement in rural China since 1990s. However, compared with elevated thermal bed in the north, it failed to achieve its optimal performance. For water heating, there is only one technology. That is solar water heater. Solar water heater has zero black carbon emission and its overall efficiency is about 46–54% (Chang et al., 2004). The gaps of solar water heater in three regions decrease from 1.03 in the north to 0.52 in the south.

4. Explaining the theory-practice gaps

The unit cost gaps in this study are mainly affected by two temporal factors—lifetime and annual utilization rate (AR). As indicated in Equation (1) in the methodology section, the shorter-than-ideal lifetime would result in a larger capital recovery factor (CRF), which would in turn lead to a larger unit cost. This means the fewer years of the technology's lifetime, the more money is needed each year to recover the initial investment. The lower-than-ideal annual utilization rate, on the other hand, would cause smaller amounts of black carbon reduced and subsequently increase the unit cost. In other words, the less frequently the technology is being used, the higher the unit cost. In the following sections, to distinguish the gaps caused by the two different factors, we will call the former the CRF gap and the latter the AR gap.

By decomposing the unit cost gaps into the CRF and AR gaps, we can locate the nine technologies on a two-dimensional plot based on their X and Y coordinates, as shown in Fig. 4. The X axis represents the CRF gap whereas the Y axis represents the AR gap. There is a special cluster located at the origin (0,0). These are technologies without unit cost gaps, which include LPG stove, elevated thermal brick bed (North), and centralized biogas system (North). The rest of the technologies have varying unit cost gaps. The CRF and AR gaps embody a complex set of sociopolitical factors that have prevented the mitigation technologies from reaching their technical potential. Those factors could be households' perceptions and behaviors, technical requirements (installation

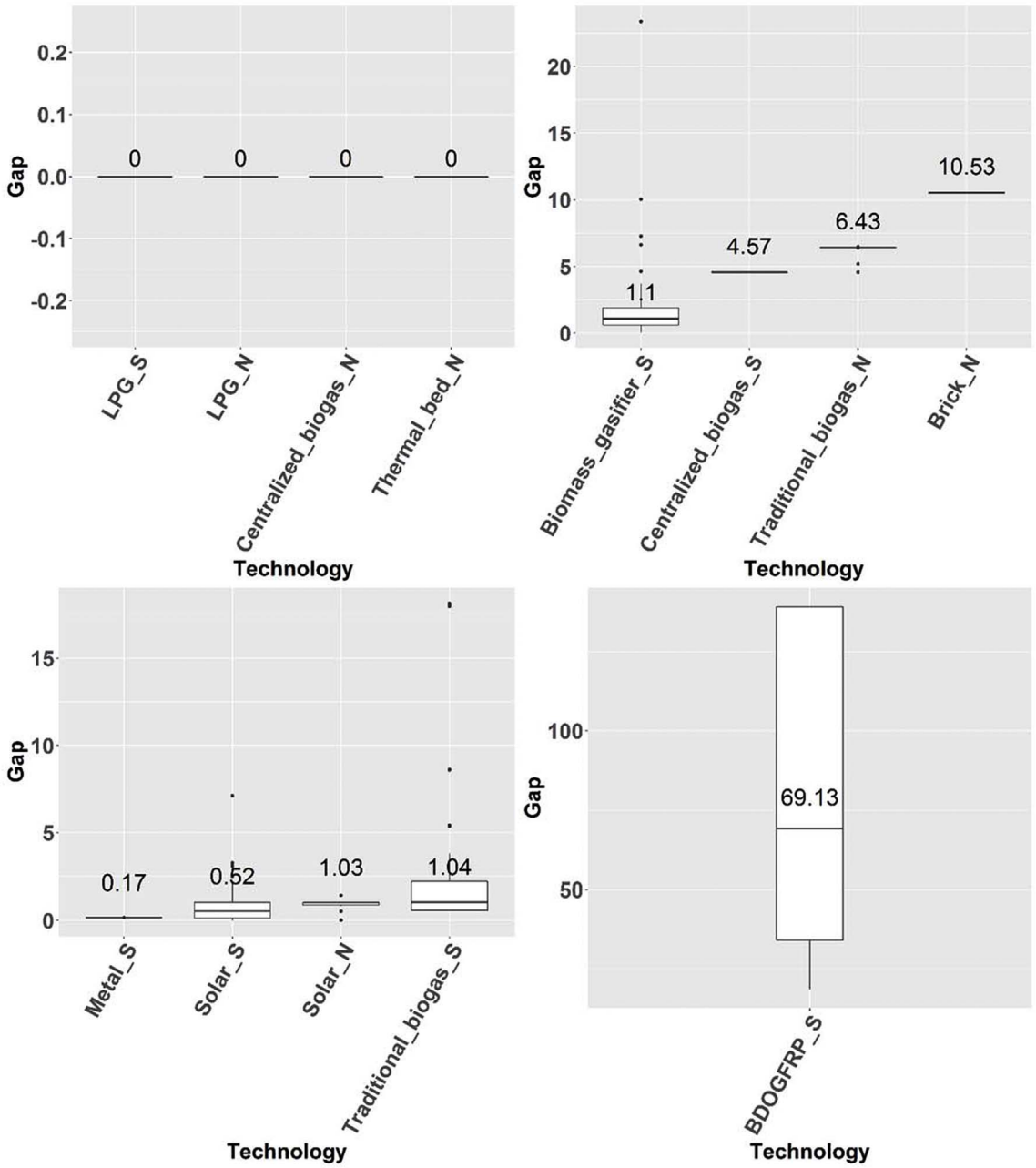

Fig. 3. Ranking of theory-practice unit cost gaps (Eq. (1)) of nine mitigation technologies.

and maintenance), and government interference.

4.1. The sole impact of the CRF gap

Located on the X axis is one group of technologies which includes improved metal stove (South), biomass gasifier (South), and improved brick stove (North). This group of technologies has a zero-AR-gap, which means that there is no difference between the expected annual utilization rate and the actual one, but they do have varying CRF gaps due to shorten lifetimes.

The reasons for the shortened lifetimes of those technologies are quite different. The improved brick stove has the largest CRF gap, up to 10.53. That is because, although the designed lifespan of the technology is 25 years, the median value of the actual lifetimes is only one year. This dramatic curtailment of the technology's lifetimes is partly caused by a lack of local initiative and partly caused by technical problems. In the case of Hebei province (the northern province), households did not choose the stove out of the concern of saving energy; they participated in the program mainly for acquiring government subsidies. Among a total of 68 respondents, 55 households (81%) admitted that they adopted the technology only for obtaining 0.5-ton free cement from the government. This lack of local interest in the technology itself also explains the fact that when later households encountered technical difficulties, they had high tendency to abandon the technology rather than making efforts to solve problems. 50 households (74%) complained that the stove did not work well because straws could not easily burn in the stove chamber. By the year 2014, only 11 households (16%) were still using the improved brick stove.

Regarding biomass gasifier (South), rather than staying in service for 15 years, the stove turned out to have a median lifespan of only one year. This shorter lifespan led to a CRF gap of 1.10. The reason why the stoves could not be used for long is that the cost of the biomass fuel (pellet) is considered by local residents to be higher than that of coal—though the unit price of compressed biomass pellets (650 CNY/

Table 2
Unit mitigation cost gaps of nine technologies in rural China.

	Province	Region	Min	Median	Mean	Max	Sample size
Biogas digester of glass fiber reinforced plastic	Guizhou	South	18.61	69.13	73.03	139.27	13
Improved brick stove	Hebei	North	10.53	10.53	10.53	10.53	68
Traditional household biogas digester	Hebei	North	4.57	6.43	6.37	6.50	58
Centralized biogas system	Guizhou	South	4.57	4.57	4.57	4.57	1
Biomass gasifier	Guizhou	South	0.05	1.10	2.24	23.38	43
Traditional household biogas digester	Guizhou Guangxi	South	0.56	1.04	3.03	18.15	65
Solar water heater	Hebei	North	0	1.03	1.05	1.43	112
	Guizhou Guangxi	South	0	0.52	0.67	7.11	172
Improved metal stove	Guizhou Guangxi	South	0.17	0.17	0.17	0.17	56
LPG stove	Guizhou Guangxi	South	0	0	0	0	44
	Hebei	North	0	0	0	0	232
Centralized biogas system	Hebei	North	0	0	0	0	1
Elevated thermal bed	Hebei	North	0	0	0	0	48

ton in 2015) is cheaper than coal, it has a much shorter burning time. After comparison, many households decided to shift to coal. By the time of the survey, 39 out of 44 users (89%) had already abandoned the technology. The five households still using the device were employers of a local pellet-manufacturing facility and had access to free pellets. Another reason why local households had shown little interest in continuously using the stove is that they did not voluntarily choose the technology at the first place. Stoves were distributed as a substitute for monetary compensation to households who had engaged in Grain for Green Project (GGP). Without alternative options, local households passively accepted the stoves although they preferred to receive the GGP compensation in cash.

The improved metal stove (South) has the smallest CRF gap of 0.17. In the survey, its lifespan was reduced to eight years in comparison with the expected 10 years. In Guizhou, 12 out of 23 households (52%) stopped using the stoves because they had limited access to firewood and straw, which are the required input materials for energy generation. The rest of the households still using the stoves attempted to substitute coal for biomass even though this type of stove is not efficient for coal combustion.

4.2. The sole impact of the AR gap

Located on Y axis is another group of technologies. This group

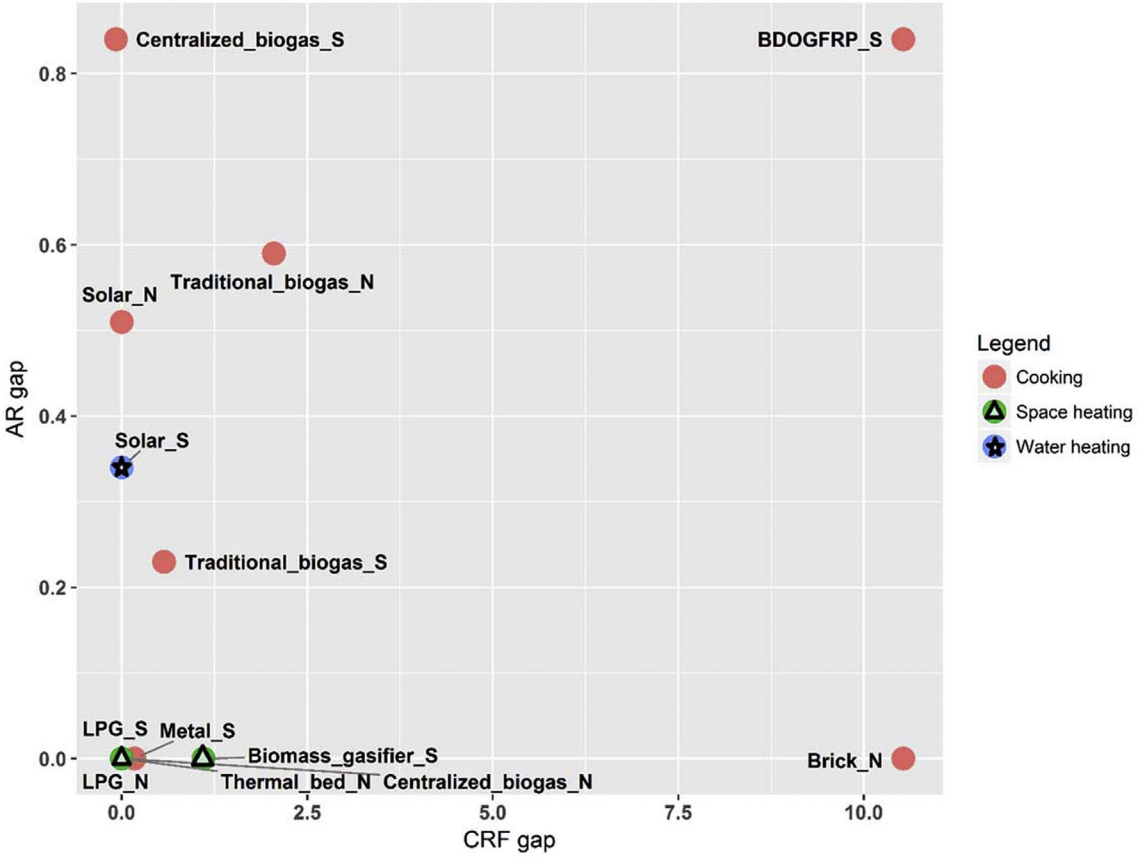

Fig. 4. The CRF and AR gaps of nine mitigation technologies.

includes solar water heater and centralized biogas system (South). Those technologies have one thing in common—zero or near-zero CRF gaps. That is because this group of technologies could reach their designed lifetimes. Thus, their unit cost gaps are mainly caused by the AR gaps.

For centralized biogas system (South), lower-than-ideal annual utilization rate was mainly caused by the lack of access to raw materials and limited biogas generation capacity of the system. Limited access to raw materials (animal and human waste) impeded the operation. Lower input led to lower-than-ideal biogas output, which in turn reduced local incentive to run the system throughout the year. At the time of fieldwork, the facility had only been used for two months in that survey year. This has contributed to an AR gap of 0.84.

The AR gap for solar water heater in the north and in the south is 0.51 and 0.34 respectively. Solar water heater is popular among rural households, because it can be easily installed and requires no input materials for energy generation. However, the solar water heater has a major drawback. Greatly depends on local climatic conditions, the device may fail to operate in winter when the temperature drops too low. This would cause an AR gap. The longer the idle period of the heater in winter, the bigger the AR gap. This study assumes the device should be used year round (365 days) because it is technically possible to use the heaters in winter if a heating stick (about 15 $/set) is installed.

In the case of Hebei, an AR gap was observed in 99% of the sampled households. Most households shut down the heaters to prevent the pipelines from freezing since the lowest temperature in winter (from December to February) can drop to as low as -6 °C. Some of households did not know the availability of heating sticks; others considered the investment too costly, or chose not to install the stick for safety concerns (primarily the problem of electricity leakage). In the south, despite the facts that the winter is less severe and that the pipelines usually do not get frozen, households still stopped using the heaters because the water out of the heater in winter is too cold to use for bath. 76% of the sampled households could not use the heater up to 365 days.

4.3. The combined impacts of the CRF and AR gaps

Technologies that are not located on the X or Y axis have both significant CRF and AR gaps. Those technologies are traditional household biogas systems and biogas digester of glass fiber reinforced plastic (South).

The biogas digester of glass fiber reinforced plastic (South) has a CRF gap of 10.53 and an AR gap of 0.84. Although the initial investment cost of this device is slightly higher than the traditional biogas digester made of cement, it is widely promoted by the government due to easy maintenance, low labor cost, stable biogas output and less temperature-dependent nature (Liu et al., 2010). However, the field survey revealed a different picture. Instead of having a designed lifetime of up to 25 years, the actual median lifespan is only one year. This shortened lifetime is caused by several technical issues. First, the digester is difficult to install. Among a total of 13 respondents, seven households (54%) failed to install the device. Second, the device is prone to damage because it is located above ground in the backyard. Five households (38%) stopped using the technology after the device was damaged. The AR gap, on the other hand, is mainly caused by a lack of input materials. The biogas system requires animal and human waste as the raw materials for energy generation. A minimum of 200 kg input materials is needed to meet the energy need for two or three months, which most households found hard to manage. Nine households (69%) reported that they could not guarantee a stable supply of animal waste and that using alternative resources such as straws would risk blocking the system.

The utilization of traditional household biogas digesters has also been plagued by many problems. Regarding the AR gap, it is climatic conditions, especially low temperature in winter, that had caused the malfunction of the digesters. The AR gap increases from 0.23 in the south to 0.59 in the north. The longer and harsher winter period in the north sets limits on the digesters' annual utilization rate, widening the AR gap. Regarding the CRF gap, it is 0.57 in the south and 2.05 in the north. These CRF gaps are caused by different lifetime gaps. Traditional household digesters are designed to last 15 years; in reality, the median lifespan is 3 years in the north and 7 years in the south. Behind those lifetime differences are sociopolitical barriers ranging from local negative perceptions to economic and technical constraints. The biogas technology firstly needs to overcome perception barriers. Some households in Guizhou refused to use biogas because they believed biogas could cause human and animal diseases. Some households in Hebei did not use the devices because they preferred the taste of food cooked by brick stoves. Second, a lack of animal and human waste is another problem. If the households stopped raising animals, they could not secure a stable supply of input materials for energy generation. They also found it difficult to shift to other alternatives because straws and rubbishes would cause system blockage. Third, the adoption of the biogas is thwarted by heavy maintenance efforts. Households often found cleaning digesters and measuring PH values and pressures quite time- and labor-consuming. Fourth, some technical obstacles prevent people from using the devices continuously. In Hebei, 5 out of 58 households (9%) could not successfully install the devices, and 26% households encountered biogas leakage.

5. Discussion

This study quantitatively measured the unit cost gaps of black carbon mitigation technologies in rural China, paying special attention to the lifetimes and annual utilization rates of those technologies. Our first-hand household survey covered three major black carbon emitting provinces (Hebei province in the North and Guizhou and Guangxi provinces in the South with and without systematic winter heating demand), seven counties, 24 villages and 695 households. The observed gaps between the in-theory and in-practice unit costs ranged between 0 and 69.13. The large gaps were found in the biogas digester of glass fiber reinforced plastic (South), improved brick stove (North) and traditional household biogas digester (North), while LPG stove, centralized biogas system (North), and elevated thermal bed had zero gaps. Although caution should be applied in attempting to adopt this study's results for entire rural China, the newly acquired quantitative knowledge could still produce better estimation than an extrapolation from other countries to China. The general shortage of such quantitative analysis in developing countries with most black carbon emissions calls for more research.

As we have come to understand, the shortened lifetime and curtailed annual utilization rate are not merely technical problems; a complex array of sociopolitical factors lies behind the theory-practice gaps. In this study, both structural and behavior factors have contributed to the curtailed lifetime and annual utilization rates and therefore the widening gaps in unit cost estimation. However, rather than viewing the structural and behavior factors as two separate sociopolitical forces, we found that in most cases household behaviors are deeply influenced by underlying institutional arrangements. The following discussions will move on to reveal how structural factors have affected the perception and utilization of the mitigation technologies in rural China.

5.1. Top-down versus bottom-up approaches

Mitigation efforts at national level often take a top-down approach, with the national government setting a mitigation plan which is then broken into small policy packages and allocated to lower-level governments. However, increasingly this top-down approach shows its limitations in that it falls short in linking goals at different levels and inflicting transaction costs. More scholars have called for the rethinking of global policy architecture "with a balance of bottom-up and top-

down elements" (Green et al., 2014). This kind of discussion also echoes the "nested governance" concept in the field of environmental management. Distributed decision-making among a hierarchy of institutions is proposed to coordinate collective efforts across scales and bolster bottom-up initiatives and self-organizing processes (Wyborn and Bixler, 2013; Ostrom, 1990).

In the case of China, the goals of improving energy efficiency and switching to cleaner fuels are first set by the national government, whereas bottom-up initiatives and management are often absent. The environmental tasks are filtered through several layers of governments and eventually passed on to rural households. Many projects are implemented to fulfil the requirements of the national government rather than meeting daily energy needs of local households. The deployment of top-down approaches may help remove the barriers to the adoption of mitigation technologies; however, insufficient engagement with rural communities have caused problems such as lack of local incentives, mismatch of resources, and inadequate management capacity. Take the traditional household biogas digester as an example. The interviews with county and village heads revealed that, instead of proactively applying for government subsidy to initiate the biogas project, they merely accepted the project as one of the assigned tasks from the top (e.g. a certain number of biogas digesters to be installed in a certain year). The task was then allocated among households on a voluntary basis or through a lottery system.

The national government is also aware of the problem. They have taken various means to ensure policy implementation at local level. Sometimes a certain amount of subsidy is provided to cover the extra cost of adopting a new technology; sometimes devices are distributed to households for free. In addition, considerable efforts have been devoted to preventing misuse of project subsidies. Often subsidies are provided in the form of free construction materials (e.g. free cements) or free raw materials (e.g. free biomass pellet). If cash is involved, households can only get the money after the installation of the required device is completed. Despite those efforts, we still found that a large share of households that had received the subsidies stopped using the technology after one year or two.

The problem of lack of local incentives is further exacerbated by the fact that mitigation devices were given to households to repay the compensation that the governments had owed to households in other environmental projects. This kind of subsidy rearrangement is found in the Grain for Green Project (GGP), which was launched by the national government in 1999. Households that had engaged in the GGP were supposed to receive monetary compensation for environmental conservation; instead, they received the stoves. The devices, distributed under this scheme, include traditional biogas digesters, biogas digesters of glass fiber reinforced plastic, improved metal stoves, and solar water heaters. Substituting devices for monetary compensation not only takes decision-making away from local communities but also reduces local incentive to participate in black-carbon-mitigation and other related environmental projects.

Busy with agenda setting, governments have failed to pay enough attention to local needs. The reluctance of local communities to adopt the mitigation technologies and their unwillingness to devote enough efforts to daily maintenance have caused low utilization rate and early breakdown of the technical devices. To narrow these gaps in lifetime and annual utilization rate, sociopolitical barriers must be removed. The government should find a balance between top-down and bottom-up approach to include local communities in political decision-making. The selection of energy systems should factor in local contexts, especially local access to raw materials for energy generation. Moreover, not only are training and knowledge sharing among households critical, regular maintenance by technical workers are also essential for guaranteeing long-term performance of adopted technologies.

5.2. Distributed versus centralized energy systems

The environmental benefits of distributed versus centralized energy generation are often debated among scholars. Against the context of climate change mitigation, the importance of distributed energy generation, complementary to centralized systems, is restressed (Pepermans et al., 2005). On one hand, distributed energy generation can result in 10% to 30% of energy saving by enabling "combined generation of heat and electricity", which in turn leads to emission reduction; on the other hand, distributed energy generation also makes it possible for households to utilize a wide range of energy sources, especially renewable energy such as solar, wind and geothermal energy (Pepermans et al., 2005). Thus, distributed energy production and use have been increasingly advocated as a promising future solution for securing energy supply and reducing greenhouse gas emissions.

However, the performance of distributed energy systems may fail our expectations as illustrated in the case of household biogas digesters in China. Both household biogas digesters and centralized biogas digesters have been promoted, and there seems to be a shift of policy focus to centralized biogas systems in recent years (Gosens et al., 2013; He et al., 2013). Regarding the choice between the two systems, one study argued that the selection should be based on local socioeconomic situations (He et al., 2013). Another study demonstrate that environmental and economic performances of household digesters are superior whereas centralized digesters "have higher energy efficiency and better social effects" (Song et al., 2014). This study illustrates the potential advantage of centralized system if we take the actual lifetimes and actual annual utilization rates into account. First, the actual lifetimes of distributed biogas digesters are much shorter. Although the lifespan of household biogas digesters is designed to be 15 years, the median lifetime is 7 years in the south and 3 years in the north. Many households stopped using the devices after encountering various technical problems. Second, regarding annual utilization rates, since biogas digesters cannot function well in a low-temperature environment (such as in winter), which again undermines the expected performance of this distributed energy system. The average in-use period is 229 days in Guizhou, 273 days in Guangxi, and 151 days in Hebei. In contrast with household digesters, centralized biogas generation systems at communal level may have a better performance. They are usually managed by professional technical staff and receive better maintenance, which allows those facilities to have longer lifespans and higher annual utilization rates. These differences may push the actual unit costs of centralized biogas system below that of distributed biogas digesters. As shown in the centralized biogas system in the north, its in-practice unit cost is estimated to be 238 $/kgBC, lower than that of household biogas digesters, which is 1041 $/kgBC in the north and 356 $/kgBC in the south. However, the better performance of centralized biogas system is not always guaranteed. The problems encountered by the centralized biogas system in the south (Guizhou province) remind us that local conditions play an important role in determining the sustainability of the centralized projects.

The fact that in practice centralized biogas system could potentially have lower costs than distributed systems can have significant policy implications. The cost-effectiveness of distributed biogas digesters in rural China may be overestimated. The theoretical assumption of well-performed distributed systems has rendered invisible other social and economic barriers, such as increasing labor opportunity cost against the context of urbanization as well as limited access to technical support. The renewable energy policies that pay little attention to those barriers may not only fail to achieve its expected environmental effects but also increase local socioeconomic burden. It is highly recommended that the feasibility of distributed biogas systems should be carefully evaluated to allow local communities to truly benefit from black carbon mitigation efforts in long terms.

The top-down approach taken by the Chinese government and the insufficient consideration of local contexts and needs could be the

major causes that had led to shortened lifetimes and limited annual utilization rate of the adopted technologies. This study could not exhaust all the mitigation technologies, nor could it examine all the assumptions in the cost assessment models. However, it quantitatively evaluated the theory-practice gap that has impeded effective mitigation efforts in China, which could also imply the situations in other developing countries.

There is no doubt that more work is needed to improve our estimation of theory-practice gaps. Uncertainties related to the results in this study are mainly caused by limited available data on emission factors and energy efficiencies of the surveyed technologies. Instead of measuring those two parameters in the field, this study depended on previous researches for emission estimation. Existing research on black carbon mitigation in rural China fell short in providing a comprehensive list of those emission parameters. Besides estimation uncertainties, this study did not quantitatively examine to what extent the lifetime and annual utilization rate have been affected by factors such as income, education level, and access to training. Acknowledging those limitations, this study invites more empirical research that investigate the theory-practice gaps of mitigation technologies and their implications for policy making.

Acknowledgement

This research was funded by the General Research Fund of the Hong Kong Research Grants Council (14619315).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2017.11.050.

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